

GLOBAL POSITIONING SYSTEM CONSTELLATION CLOCK PERFORMANCE

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Abstract

The Naval Research Laboratory (NRL) conducts comprehensive analyses of the Global Positioning System (GPS) atomic frequency standards under the sponsorship of the GPS Joint Program Office (JPO) and in cooperation with the 2nd Space Operations Squadron (2SOPS) at the Master Control Station (MCS) in Colorado Springs, Colorado. The purpose of the analyses is to determine the performance of the timing signals originating with the atomic frequency standards carried aboard the space vehicles. Metrics used in the analyses and presented in this paper include frequency, drift, and stability histories and stability profiles based on the Allan and Hadamard variances. Also presented in this paper are comparisons of performance based on the broadcast as well as the precise post-fit ephemerides.

INTRODUCTION

Performance of the Navstar space vehicle clocks is summarized using a multi-year database that includes data collected to 1 October 2003. This continuing work is sponsored by the GPS Joint Program Office and is done in cooperation with the GPS Master Control Station. The measurements were collected from a network of Air Force, National Imagery and Mapping Agency (NIMA), and International GPS Service (IGS) monitor stations. The NIMA Washington, D.C. monitor station, located at the United States Naval Observatory (USNO), uses the Department of Defense (DoD) Master Clock as the time reference. The results of the NRL analyses of the space vehicle and monitor station clocks are used by the GPS Master Control Station to set parameters in the Kalman filter, thereby improving navigation and time transfer performance [1]. The results of the NRL analyses are reported to the GPS Joint Program Office and to the Master Control Station and are made available to the GPS working group community via an NRL Web site.

METHODOLOGY

The network of monitor stations, depicted in Figure 1, consists of six USAF, 13 NIMA, and one IGS monitor stations. The offset of each monitor station clock with respect to the DoD Master Clock is computed using Multiple-Path Linked Common-View Time Transfer (LCVTT) [2]. The advantages of using multiple paths are that the absence of measurements at one station does not result in the loss of time transfer data for the remaining stations in the network and the averaging of multiple, independent measurements results in a reduction of the measurement noise. The offset of each monitor station clock from the

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DoD Master Clock is combined with the offset of the space vehicle clocks from each monitor station to produce the offset of each space vehicle clock from the DoD Master Clock. This process results in multiple measurements of the space vehicle clock offset at each 15-minute epoch. The measurements are then averaged at each epoch to get continuous coverage of each Navstar clock with respect to the DoD Master Clock [3]. The continuous coverage measurements are then used to compute the frequency offset, drift offset, frequency stability profiles, and frequency stability histories for the Navstar clocks using the NRL Clock Analysis Software System (CLASS). CLASS is a complex set of software analysis tools comprised of over 400,000 lines of code that was developed at NRL over the last 19 years. The current active database includes data for the 81 Block II/IIA/IIR clocks that have been activated out of the 136 clocks on 36 space vehicles. Archived data are maintained for 35 of the 37 Block I clocks on 10 space vehicles.

CONSTELLATION OVERVIEW

A summary of the operational Navstar clocks in the GPS constellation as of October 2003 is presented in Figure 2. Each Block II/IIA/IIR space vehicle is shown by plane, position in the plane, and type of clock that was operating on each space vehicle. Eighteen of the 28 clocks operating were rubidium atomic frequency standards (RAFS) and 10 were cesium atomic frequency standards (CAFS). Of the 18 RAFS, eight are on the new Block IIR space vehicles.

The total operating time for each of the Navstar space vehicles since the space vehicle was inserted into the constellation is shown in Figure 3. Twenty-six space vehicles have met or have exceeded the required Block II/IIA mean mission duration of 6 years. Twenty-two space vehicles have exceeded 8 years of operation, 20 have exceeded 10 years of operation, and six have exceeded 12 years of operation. Eight Block II/IIA space vehicles, Navstars 14, 16, 18, 19, 20, 21, 22, and 28, have been decommissioned. Navstar 28 was the only space vehicle that did not meet the required mean mission duration before being decommissioned. The average lifetime of the Block II/IIA space vehicles is 10.4 years.

The number of clocks that have been placed in operation on each of the active space vehicles, since the space vehicle was inserted into the constellation, is shown in Figure 4. Of the active space vehicles, ten are on the first clock, 11 are on the second clock, three are on the third clock, and four, Navstars 17, 24, 31, and 32, are on the fourth clock. While Navstar 43 shows two clocks placed into operation, one was turned on for test purposes and then switched off. It was a good clock and can be reactivated when the need arises. The Block IIR space vehicles are equipped with only three clocks, all RAFS. The Block II and IIA space vehicles each have four clocks, two CAFS and two RAFS.

In Figures 5 and 6 are shown the frequency standard operating schedule for the clocks in Planes B and D. Navstar 13 can be seen to have used only one clock in 14 years of operation, while Navstars 17 and 24 can be seen to have used all four clocks.

The operating lifetime, or length of service, of the clocks that were operating as of 1 October 2003 is shown in Figure 7. The red bars refer to Block II/IIA cesium clocks, the blue bars to Block II/IIA rubidium clocks, and the green bars to Block IIR rubidium clocks. Six clocks, all cesium atomic frequency standards, have exceeded 8 years of continuous operation. The cesium clock on Navstar 13 has exceeded 14 years of continuous operation. One of the Block IIR rubidium clocks, on Navstar 43, has exceeded 6 years of continuous operation. As of 1 October 2003, the average age of the currently active CAFS is 9.0 years compared to an average age of 3.3 years and 2.9 years respectively for the Block IIA and Block IIR RAFS.

NAVSTAR TIMING SIGNAL MEASUREMENTS

The phrase “Timing Signal” is used rather than “Clock Offset” because the output of the atomic frequency standard is further modified by the electronics before being broadcast by the space vehicle. The output signal from the atomic frequency standard is fed to the Frequency Standard Distribution Unit (FSDU) for the Block II/IIA space vehicles and to the Time Keeping System (TKS) for the Block IIR space vehicles. The TKS provides the additional capability of adjusting the frequency and drift of the timing signal. Where this capability has been employed, the offset of the frequency and drift from the DoD Master Clock have been adjusted to less than $3 \text{ pp } 10^{12}$ and to less than $2 \text{ pp } 10^{14}/\text{day}$ respectively.

FREQUENCY STABILITY MODELS

NRL currently employs two time-domain models to estimate the frequency stability of the timing signals. The Allan deviation is normally used in the analysis of cesium clocks, which exhibit extremely low values of drift. The Hadamard deviation adaptively removes the drift and is, therefore, applied to rubidium clocks, which are typically characterized by large values of drift. The frequency stability is computed as a function of sample time to determine the long-term and short-term characteristics of the clocks. Because of the dominance of measurement noise at the shorter sample times, from 15 minutes to 12 hours, the estimates of stability for these sample times are characteristic more of the noise than of the timing signal.

Since the Navstar clocks are expected to operate on orbit for a period of years, an analytical method of determining frequency stability history was developed to detect nonstationary behavior and to examine frequency stability as a function of time [4]. The frequency stability history is obtained by performing an N-day moving average of the sequence of squared first differences (Allan deviation) or squared second differences (Hadamard deviation) of frequency offset measurements separated by the sample time. The stabilities are computed for a specified sample time, window width, and time span. The sample times of interest are usually 6-hours and 1-day, and the window width is chosen to insure sufficient averaging to achieve confidence in the estimates. The time spans may be over months or years depending on the type of analysis being performed. In all cases, discontinuities in the data for which the cause is unknown are left uncorrected.

FREQUENCY STABILITY PROFILE

Frequency stability profiles were estimated for sample times of one to 18 days for the 6 months ending 1 October 2003. In Figures 8 and 9, are shown the frequency stability profiles based on the Allan and Hadamard variances respectively for all clocks in the constellation that were active as of 1 October 2003. In Figure 8, the estimates of stability for a sample time of 18 days can be seen to fall into two groups. Because of the dominance of the drift in the timing signals originating with the Block II/IIA rubidium clocks, the stability estimates of these timing signals for a sample time of 18 days all fall above $4 \text{ pp } 10^{13}$. By contrast, the stability estimates for the timing signals originating with the Block II/IIA cesium clocks and the Block IIR rubidium clocks all fall below $2 \text{ pp } 10^{13}$. With the removal of the drift inherent in the computation of the Hadamard deviation shown in Figure 9, the stability estimates at a sample time of 18 days for all timing signals showed improvement. The improvement was greatest, of course, for the timing signals originating with the Block II/IIA rubidium clocks. The most stable timing signals can be seen to be those originating with the Block IIR rubidium clocks on Navstars 51 and 54.

Figures 10 and 11 compare the stability estimates, based on the Allan and Hadamard deviations respectively, for the timing signals originating with the Block II/IIA rubidium clocks. Again, because of the dominance of the drift in the timing signals originating with Block II/IIA rubidium clocks, the stability estimates, even for a sample time of 1 day, show improvement when the drift is adaptively removed in the computation of the Hadamard deviation. In Figure 11, the most stable timing signals for a sample time of 1 day are those for Navstars 26, 27, 29, 30, 34, and 37.

Figures 12 and 13 compare the stability estimates, based on the Allan and Hadamard deviations respectively, for the timing signals originating with the Block IIR rubidium clocks. Not surprisingly, the most improvement in Figure 13 is seen for the timing signals from Navstars 45 and 56, neither of which has had the drift adjusted by the Master Control Station. With the drift adaptively removed in the computation of the Hadamard deviation, the most stable timing signals for a sample time of 1 day are those from Navstars 41, 54, and 56, which have a stability near $1.3 \text{ pp } 10^{14}$. The least stable for a sample time of 1 day is the timing signal for Navstar 44. Its stability estimate of $7.2 \text{ pp } 10^{14}$ for a sample time of 1 day failed to meet the GPS specification of $6 \text{ pp } 10^{14}$.

SYSTEMATICS REMOVAL WITH BROADCAST ORBIT

The timing signals from several space vehicles in the constellation have shown evidence of a strong systematic at the orbital period. The oscillation can be seen in the stability profile at the higher time resolution obtained when it is exhaustively calculated every 15 minutes over several days. Since there is no provision in the space vehicle for modeling an oscillation in the timing signal, the MCS has attempted to compensate for the systematic by adjusting the parameters describing the broadcast orbit. To determine how well this effort is succeeding, a comparison was made between stability profiles based on data computed using both the broadcast and the precise orbits [5].

In Figures 14 to 17 are shown the frequency stability profiles based on the Hadamard deviation for four timing signals in the constellation. Each figure contains two profiles exhaustively calculated every 15 minutes from 15 minutes to 40 hours. The first two figures (for Navstars 23 and 36) correspond to cesium frequency standards, and the last two figures (for Navstars 38 and 51) correspond to rubidium frequency standards. Three of the timing signals, those from Navstars 23, 36, and 38, show evidence of a strong systematic at the orbital period. By contrast, the timing signal from Navstar 51 showed no evidence of a systematic.

In Figures 14 and 16, corresponding to the timing signals from Navstars 23 and 38, the oscillation has been largely removed in the profile based on the broadcast orbit. In Figure 15, corresponding to the timing signal from Navstar 36, the oscillation is still present in the profile based on the broadcast orbit, but is reduced in amplitude. For all three timing signals showing evidence of a strong systematic, use of the broadcast orbit resulted in general improvement in the stability. In Figure 17, as expected, use of the precise orbit for a timing signal with no systematic yielded uniformly better estimates of the stability.

FREQUENCY STABILITY HISTORY

In Figures 18 to 22 are shown the 1-day frequency stability histories for the timing signals from five space vehicles in the constellation. In all but one case, the histories are estimated over the lifetime of the clock. The exception is Navstar 13, which was activated 18 June 1989, 6 years before the NIMA Washington, D.C. monitor station located at the U.S. Naval Observatory began operation, thereby making pos-

sible by time transfer the continuous calculation of the Navstar timing signal offset from the DoD Master Clock.

Figure 18 shows the 1-day frequency stability of the Navstar 13 timing signal to be within the Block II cesium specification of $2 \text{ pp } 10^{13}$ for the period of 8 years since 1 June 1995. Figure 19 shows the 1-day stability history for the Navstar 41 timing signal to be within the Block IIR rubidium specification of $6 \text{ pp } 10^{14}$ during 98.3 percent of the time. It failed to meet the specification briefly on three occasions separated from each other by about 11 months. Figure 20 shows the 1-day stability history for the Navstar 44 timing signal to be within the Block IIR rubidium specification only 37.7 percent of the time. Figure 21 shows the 1-day stability history for the Navstar 45 timing signal to be within the Block IIR rubidium specification 89.7 percent of the time, with the stability failing to meet the specification briefly on four occasions. Finally, Figure 22 shows the 1-day stability history for the Navstar 51 timing signal to be within the Block IIR rubidium specification 100 percent of the time.

FREQUENCY STABILITY SUMMARY

Figures 23 and 24 show the 1-day frequency stability estimates based on the Allan and Hadamard variance for the timing signals from all 28 Navstar space vehicles in the constellation. The Allan deviation in Figure 23 shows that all Block II/IIA timing signals meet the Block II/IIA cesium specification of $2 \text{ pp } 10^{13}$ and the Block II/IIA rubidium specification of $5 \text{ pp } 10^{13}$. Figure 24 shows that all but one Block IIR timing signal meet the Block IIR rubidium specification of $6 \text{ pp } 10^{14}$. The exception is the timing signal for Navstar 44. Six-hour and 1-day frequency stabilities are calculated for each Navstar timing signal using 1 month of data.

The stability ranking of all operational Navstar space-vehicle timing signals for the month of September 2003 is presented in Figure 25. The chart shows, in the front row, the ranking in order of stability of the 1-day frequency stability estimates based on the Hadamard deviation. The back row shows for comparison the corresponding frequency stability estimates for a sample time of 6 hours. The timing signal from the Block IIR rubidium clock on Navstar 56 was the most stable clock in the GPS constellation with a 1-day stability of $1.4 \text{ pp } 10^{14}$ for the month of September. The timing signal from the Block IIA cesium clock on Navstar 32 was the least stable with a 1-day stability of $1.4 \text{ pp } 10^{13}$. The 6-hour frequency stability estimates are more sensitive to measurement noise and systematic effects that may be present in the data. Significant differences can be observed between the 6-hour frequency stability estimates for all Navstar space-vehicle timing signals as compared to the 1-day estimates. The 6-hour frequency stability estimates varied from $6.4 \text{ pp } 10^{14}$ to $1.2 \text{ pp } 10^{12}$.

CONCLUSIONS

The lifetimes of the Navstar clocks are such that the mean mission duration specification for the space vehicles has been met in all cases. The only exceptions are those space vehicle failures not attributable to the clocks. Forty-seven of 80 Block II/IIA clocks have been operated, while 10 of 24 Block IIR clocks have been operated. The 1-day frequency stability of all of the Navstar clocks in the GPS constellation, as of 1 October 2003, was better than $1.4 \text{ pp } 10^{13}$. The best timing signal was that originating with the Navstar 54 Block IIR rubidium clock, which had a 1-day stability of $1.4 \text{ pp } 10^{14}$.

The average lifetime for all currently activated Navstar atomic clocks is 4.4 years. The oldest active clock in the constellation is the Navstar 13 Block II cesium clock, which has been continuously operated for more than 14 years. The oldest active Block IIR rubidium clock in the constellation is the Navstar 43

clock Serial No. 6, which has been operated for more than 6 years. The average age of the 10 cesium clocks operating on 1 October 2003 was 9.0 years, compared to an average age of 3.3 years for the 10 Block II/IIA rubidium clocks and 2.9 years for the eight Block IIR rubidium clocks operating on 1 October 2003.

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- [1] S. T. Hutsell, W. G. Reid, J. D. Crum, H. S. Mobbs, and J. A. Buisson, 1997, “*Operational Use of the Hadamard Variance in GPS*,” in Proceedings of the 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, 3-5 December 1996, Reston, Virginia, USA (U.S. Naval Observatory, Washington, D.C.), pp. 201-214.
- [2] W. G. Reid, 2000, “*Multiple-Path Linked Common-View Time Transfer*,” in Proceedings of the 31st Annual Precise Time and Time Interval (PTTI) Systems and Applications Meeting, 7-9 December 1999, Dana Point, California, USA (U.S. Naval Observatory, Washington, D.C.), pp. 43-53.
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- [4] T. B. McCaskill, 1997, “*Analysis of the Frequency Stability History of GPS Navstar Clocks*,” in Proceedings of the 1997 IEEE International Frequency Control Symposium, 28-30 May 1997, Orlando, Florida, USA (IEEE Publication 97CH36016), pp. 295-303.
- [5] T. B. McCaskill, W. G. Reid, G. Wilson, O. J. Oaks, H. E. Warren, and J. A. Buisson, 1993, “*Effect of Broadcast and Precise Ephemerides on Estimates of the Frequency Stability of Navstar Clocks*,” in Proceedings of The Institute of Navigation (ION) GPS-93 Conference, 22-24 September 1993, Salt Lake City, Utah (Institute of Navigation, Alexandria, Virginia), pp. 121-128.

NRL Clock Analysis Data Input

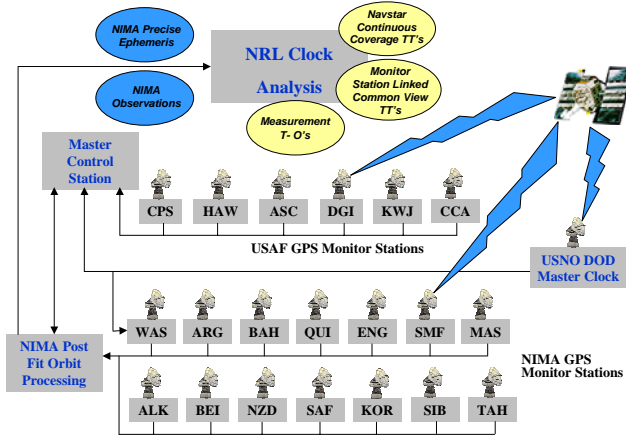


Figure 1.

GPS Satellite Position and Clock Type as of 30 September 2003

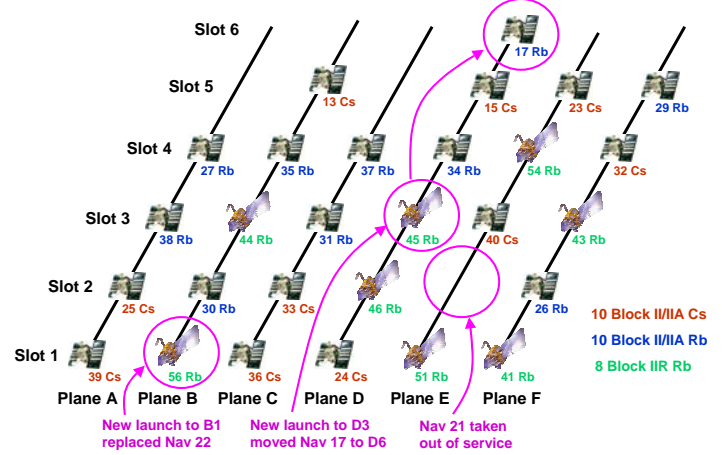


Figure 2.

Total Operating Time of Block II/IIA/IIR NAVSTAR Space Vehicles as of October 2003

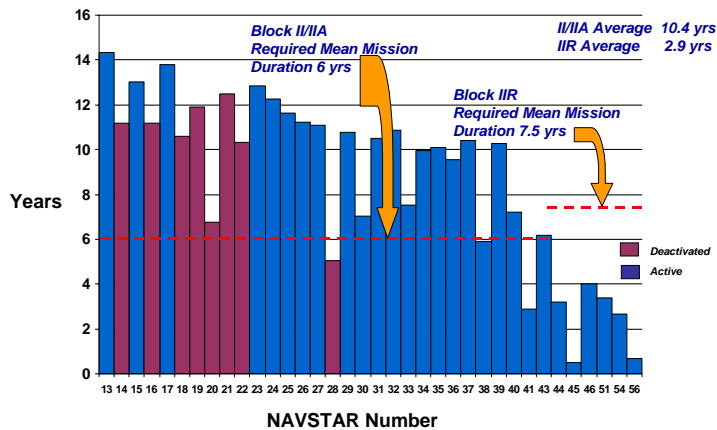


Figure 3.

Number of Clocks Operated Since Insertion on Operational Space Vehicles as of October 2003

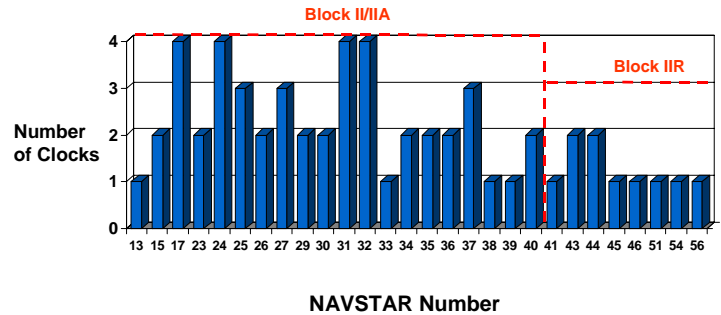


Figure 4.

FREQUENCY STANDARD OPERATING SCHEDULE NAVSTAR GPS CONSTELLATION PLANE B

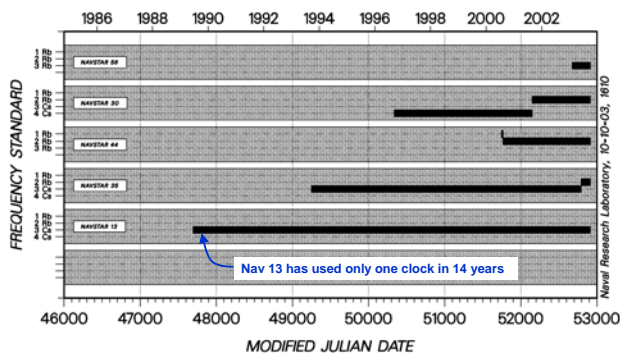


Figure 5.

FREQUENCY STANDARD OPERATING SCHEDULE NAVSTAR GPS CONSTELLATION PLANE D

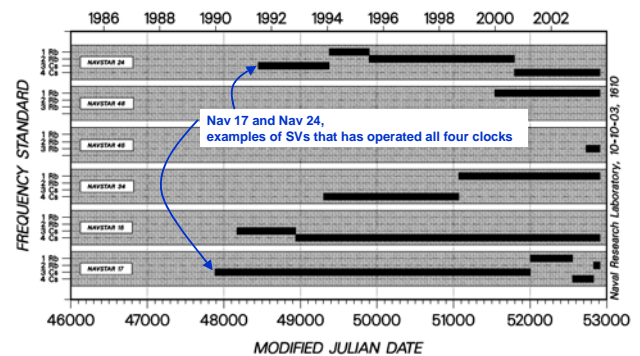


Figure 6.

Operating Lifetime of Current NAVSTAR Clocks as of October 2003

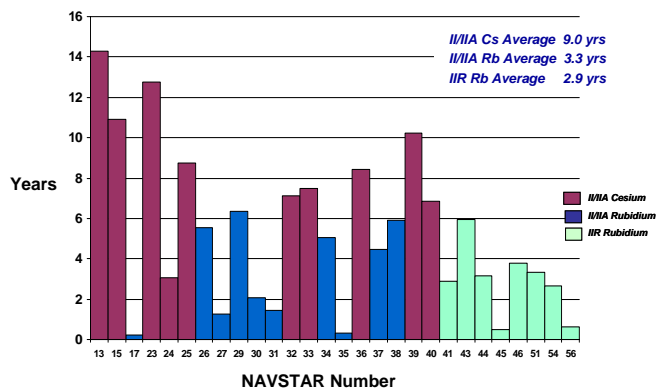


Figure 7.

FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM DoD Master Clock 1-APR-03 to 1-OCT-03

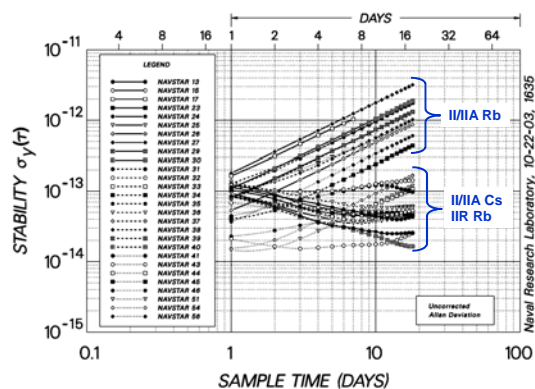


Figure 8.

FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM DoD Master Clock 1-APR-03 to 1-OCT-03

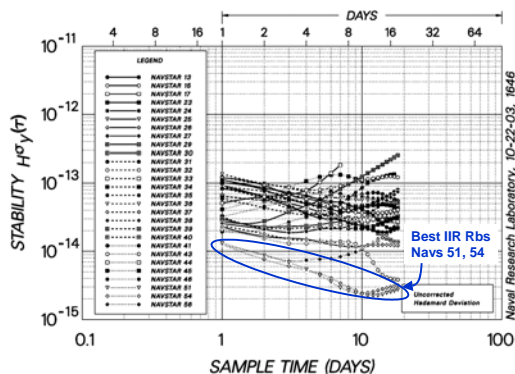


Figure 9.

FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM DoD Master Clock Block II/IIR RAFS 1-APR-03 to 1-OCT-03

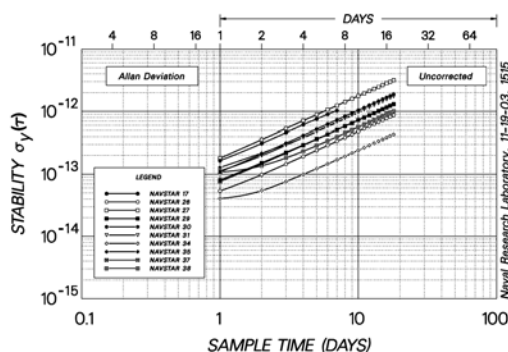


Figure 10.

FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM DoD Master Clock Block II/IIR RAFS 1-APR-03 to 1-OCT-03

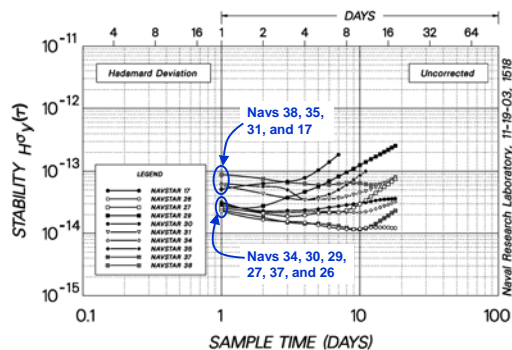


Figure 11.

FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM DoD Master Clock Block IIR RAFS 1-APR-03 to 1-OCT-03

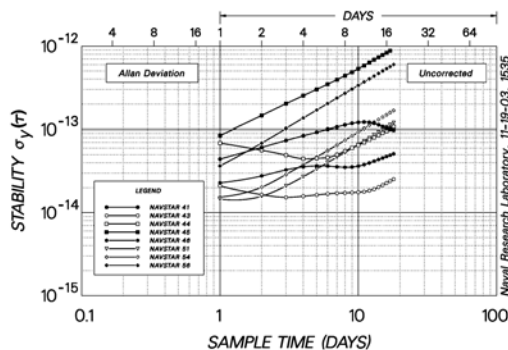


Figure 12.

FREQUENCY STABILITY OF NAVSTAR TIMING SIGNAL OFFSET FROM
DoD Master Clock
Block IIR RAFS
1-APR-03 to 1-OCT-03

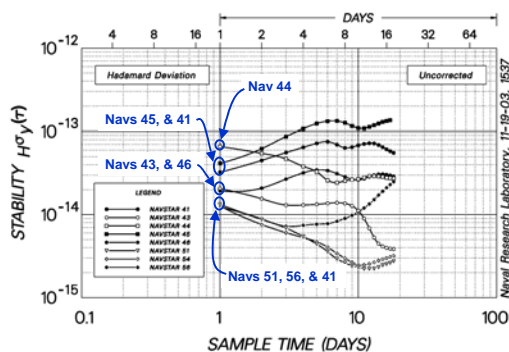


Figure 13.

NIMA Precise Orbits vs. Broadcast Orbits
(NAV/PRN 23/23 - UTC(USNO) linear removed)

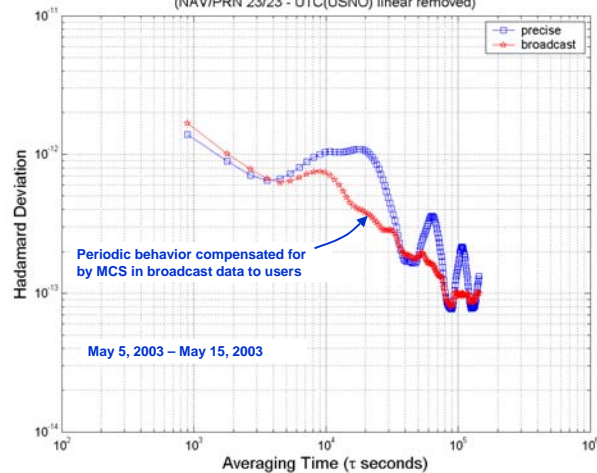


Figure 14.

NIMA Precise Orbits vs. Broadcast Orbits
(NAV/PRN 36/6 - UTC(USNO) linear removed)

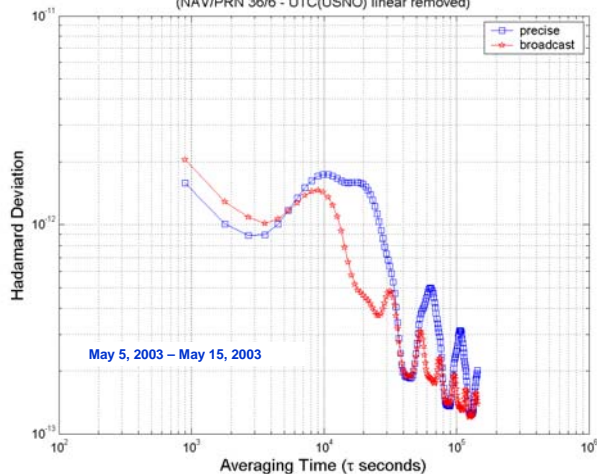


Figure 15.

NIMA Precise Orbits vs. Broadcast Orbits
(NAV/PRN 38/8 - UTC(USNO) linear removed)

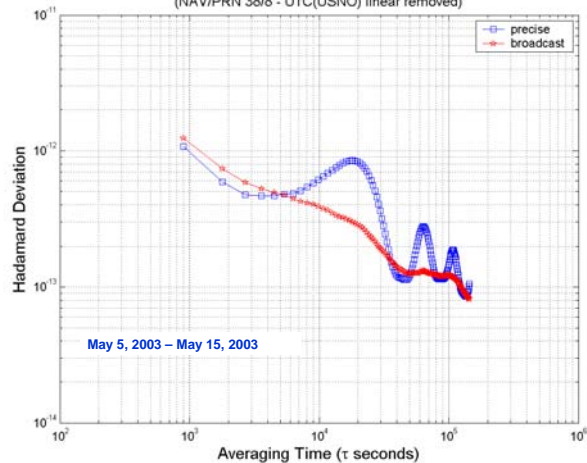


Figure 16.

NIMA Precise Orbits vs. Broadcast Orbits
(NAV/PRN 51/20 - UTC(USNO) linear removed)

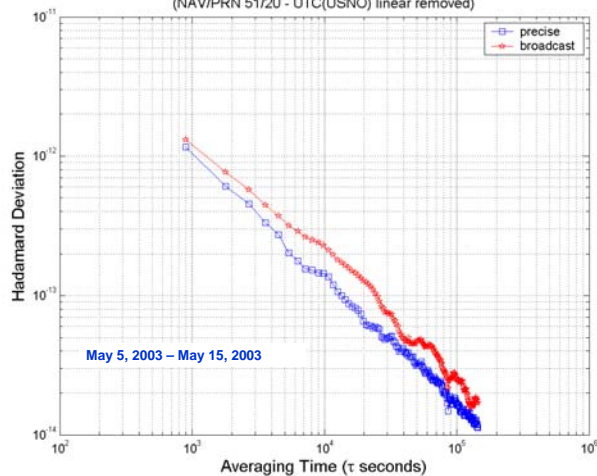


Figure 17.

FREQUENCY STABILITY HISTORY OF NAVSTAR 13 TIMING SIGNAL OFFSET FROM
DoD Master Clock Using
CAFS Serial No. 14
Sample Time: 1 day Window Width: 4 days

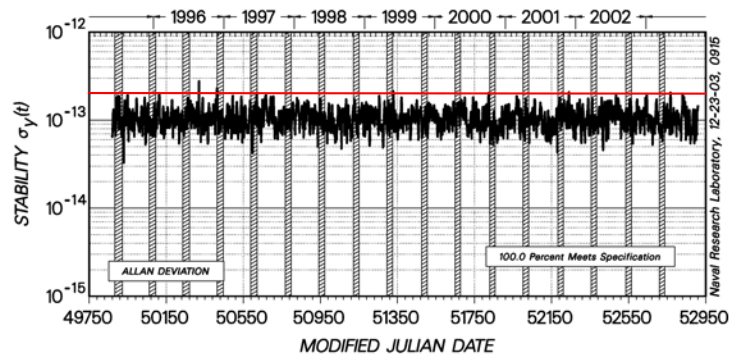


Figure 18.

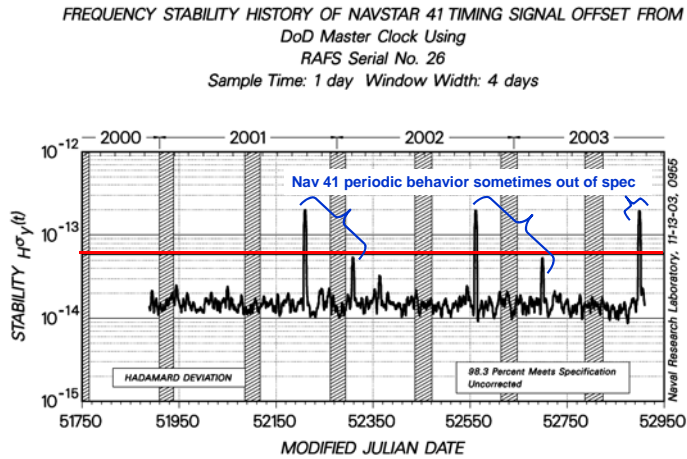


Figure 19.

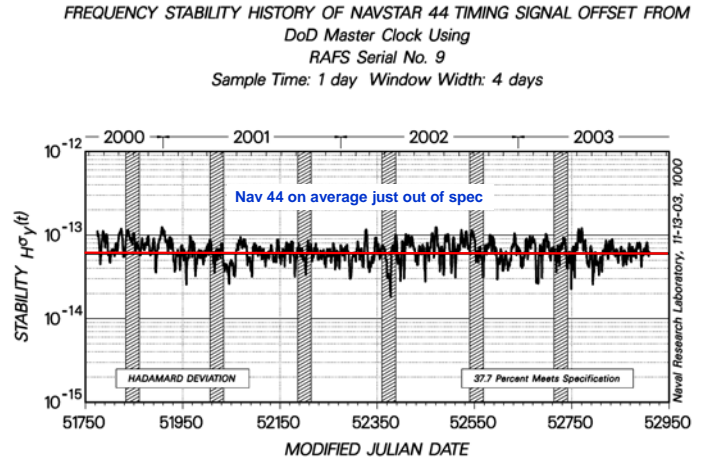


Figure 20.

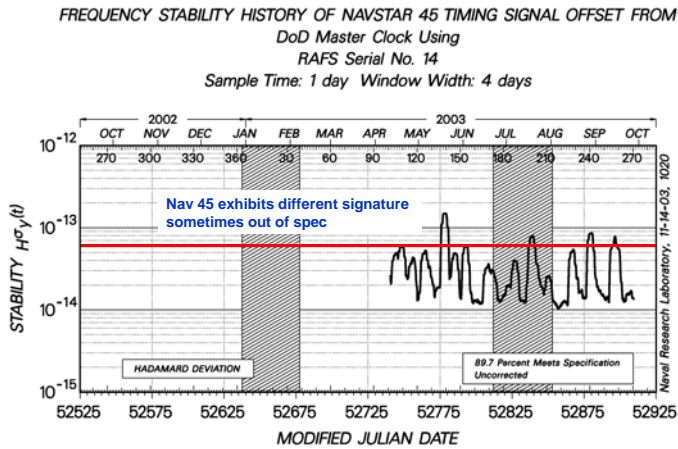


Figure 21.

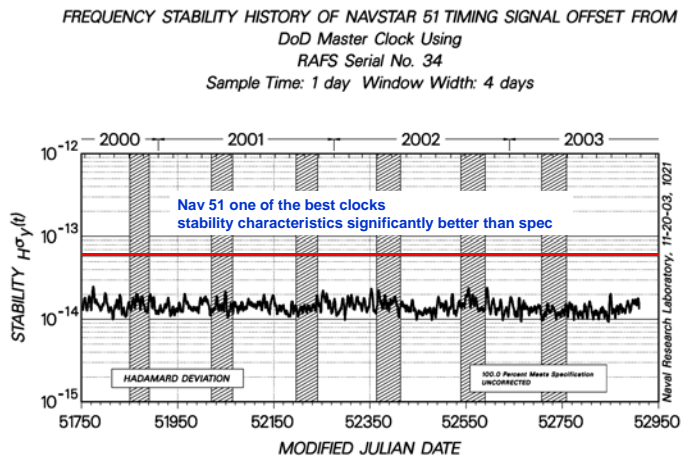


Figure 22.

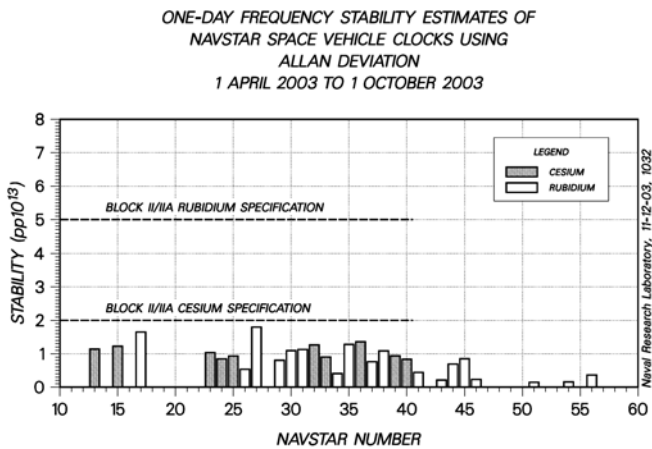


Figure 23.

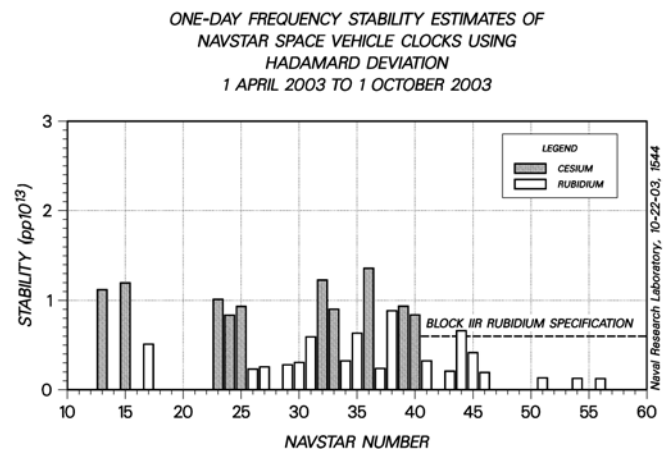


Figure 24.

**One-Day and Six-Hour Frequency Stability of
Navstar Timing Signals Using Hadamard Deviation
1 September 2003 to 1 October 2003
(Ranked by One-Day)**

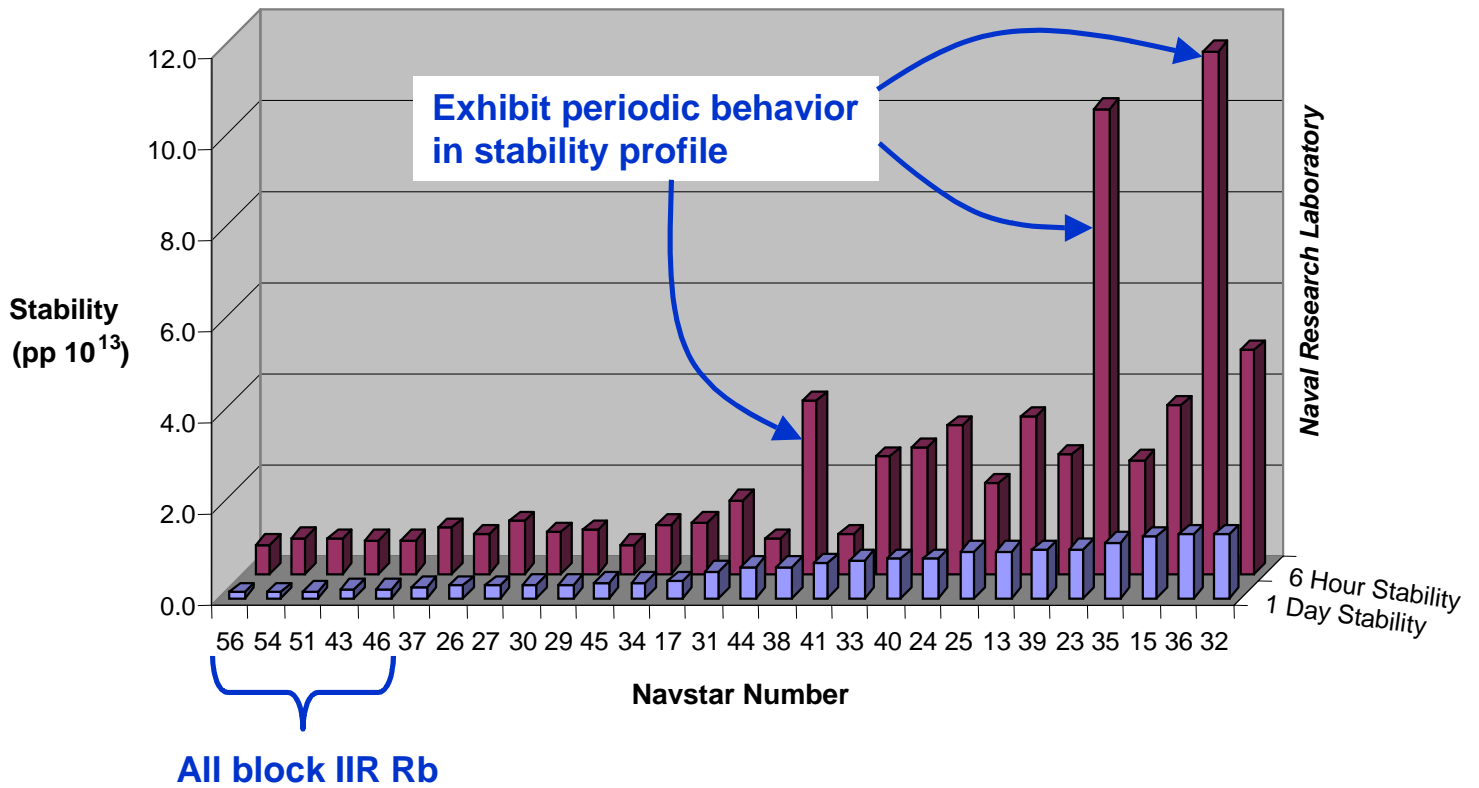


Figure 25.

QUESTIONS AND ANSWERS

DAVE HOWE (National Institute of Standards and Technology): The compelling question is what is different about the excellent rubidium? It is very good.

JAY OAKS: I guess Bill Riley pointed out that they all have their own characteristics. I don't think anybody has pinpointed, from a manufacturer's standpoint, reasons for why some are much better than others.

BILL RILEY (Symmetricom): I would only point out that the difference is awfully sharp. Looking back with 20/20 hindsight and so forth, the differences do show up in the original acceptance test data. Ours was supposed to be, and actually was, a profit-making clock making operation. When clocks met specifications, they were shipped. But some were better than others. The ones that have shown the best performance in orbit showed the best acceptance test data.

That is good, I think, because it means that one could cherry pick or tighten up specifications. There would be some expense involved in that. There is even, I guess, some possibility of some retrofit that kind of never happened, right, John? There was talk about some of the clocks, because there are a lot of clocks in storage, that there was time to go back and take another pass through them, if you will, making the ones that were not as good better. But that again was a matter of money, because they do indeed meet the requirements. I guess that's the bottom line.

OAKS: And I don't even know how you would address taking one apart to figure out what causes one thing over another, because each characteristic that we've seen is different. So I don't know how you would address that.

RILEY: Right, we did have some ideas about what made one different from another. These are pretty subtle things, and we have gotten them a lot better over the years. We think we can make them even better. They seem to be doing the job. I guess that is really what ultimately matters.

GARY DIETER (Boeing): Jay, before you sit down, could you maybe talk for a moment about some of the plans your team might have over the next year?

OAKS: Yes. We are going through a migration from older computer technology, VMS workstations to the new PC technology. Some of the data that we have shown here are from the PC platforms. We are trying to take advantage of new data sources like an online broadcast ephemeris, and to be able to do comparisons as shown here in our data. We expect that we will have a good portion of that migration done by the end of this fiscal year, by next October.